

## A RADIAL VELOCITY AND CALCIUM TRIPLET ABUNDANCE SURVEY OF FIELD SMALL MAGELLANIC CLOUD GIANTS

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## ABSTRACT

We present the results of a pilot wide-field radial velocity and metal abundance survey of red giants in ten fields in the Small Magellanic Cloud (SMC). The targets lie at projected distances of 0.9 and 1.9 kpc from the SMC centre ( $m - M = 18.79$ ) to the North, East, South and West. Two more fields are to the East at distances of 3.9 and 5.1 kpc. In this last field we find only a few to no SMC giants, suggesting that the edge of the SMC in this direction lies approximately at 6 kpc from its centre. In all eastern fields we observe a double peak in the radial velocities of stars, with a component at the classical SMC recession velocity of  $\sim 160 \text{ km s}^{-1}$  and a high velocity component at about  $200 \text{ km s}^{-1}$ , similar to observations in HI. In the most distant field (3.9 kpc) the low velocity component is at  $106 \text{ km s}^{-1}$ . The metal abundance distribution in all fields is broad and centred at about  $[\text{Fe}/\text{H}] \sim -1.25$ , reaching to solar and possibly slightly supersolar values and down to  $[\text{Fe}/\text{H}]$  of about  $-2.5$ . In the two innermost (0.9 kpc) Northern and Southern fields we observe a secondary peak at metallicities of about  $\sim -0.6$ . This may be evidence of a second episode of star formation in the centre, possibly triggered by the interactions that created the Stream and Bridge.

*Subject headings:* Magellanic Clouds — galaxies: stellar content

## 1. INTRODUCTION

The Small Magellanic Cloud (hereafter SMC) is, together with the Large Magellanic Cloud (LMC) the nearest dwarf irregular galaxy to our own, and provides an invaluable laboratory to study star formation and chemical evolution in low mass galaxies. There is recent evidence that the LMC and SMC are on their first pass around the Milky Way and that the SMC may not be bound to the LMC (Kallivayalil et al. 2006a,b; Besla et al. 2007). The SMC may be a rare example of a comparatively isolated dwarf galaxy and possibly even a surviving fragment from the era of reionization. However, the SMC has also been interacting with the LMC during the past few Gyrs and these interactions have modulated the recent star formation history of both galaxies (e.g., Bekki & Chiba 2005, 2009 and references therein).

The SMC is best modelled as an old dwarf spheroidal galaxy possessing a gaseous disk (Bekki & Chiba 2009) that has been distorted by star formation and tidal stresses, giving the galaxy its present irregular appearance (e.g., Harris & Zaritsky 2004; Cioni et al. 2006). The distribution and chemical abundances of field stars in the SMC thus provide clues to its star formation history. Open questions include: whether there is an ‘edge’ to the SMC, the metallicity distribution of its field stars, the presence of a metal abundance gradient and whether a metal-poor halo exists around the SMC or other dwarf galaxies as it does around the Milky Way and other giants.

Stars belonging to the SMC have been found along the Magellanic Bridge; an old and intermediate age population out to  $5^\circ$  but only a young population at  $\sim 6.5^\circ$  (Harris 2007). Noël & Gallart (2007) explored three fields to the South of the SMC identified SMC stellar sequences belonging to the intermediate age population out to 6.5 kpc from the SMC centre. In other galaxies, Munoz et al. (2006) observed LMC stars as

far as  $23^\circ$  from its centre. Extended stellar envelopes are also detected around other dwarfs (e.g., Minniti & Zijlstra 1996; Vansevicius et al. 2004; Hidalgo et al. 2009, but at least in some cases, these are actually tidal in origin (Munoz et al. 2006). Although stars are proved to exist at large projected distances in many nearby dwarfs, these objects may not represent a classical metal-poor halo as is encountered in the Milky Way or M31. For instance, in the LMC stars studied by Munoz et al. (2006), the metallicity distribution is broad and centred around  $[\text{Fe}/\text{H}] \sim -1$ , with a large range of ages (Gallart et al. 2004), unlike the largely old and metal-poor stars that are believed to populate the outer halos of giant galaxies. The SMC itself appears to have formed stars quickly at early epochs reaching a metallicity of  $\sim -1$  and to have then suffered a series of star formation episodes over the past 3 Gyrs, after a period of quiescence, which have produced younger stellar populations and more metal rich stars (Harris & Zaritsky 2004).

In the innermost regions of the SMC, Carrera et al. (2008) found an average metallicity of  $[\text{Fe}/\text{H}] \sim -1$ , in agreement with previous studies, but also claimed to have detected a metal abundance gradient (richer inward), arguing that this is related to an age gradient, with younger (and more metal rich) stars towards the SMC centre. While this agrees with the earlier work of Piatti et al. (2007a,b), the study of SMC clusters and field giants (in the proximity of clusters) by Parisi et al. (2008, 2010), as well as the work by Cioni (2009) on the C/M ratio of AGB stars in the SMC, do not support the existence of the metal abundance gradient claimed by Carrera et al. (2008).

In this *Letter* we report on a pilot program for an extensive radial velocity and Calcium Triplet survey of the SMC, based on data collected during a similar survey of the Galactic Bulge. The observations and data reductions are described in the next section, while we present the main results and our discussion in the following sections. We adopt the most recent distance modulus of 18.79 for the SMC (Szewczyk et al. 2009).

## 2. OBSERVATIONS

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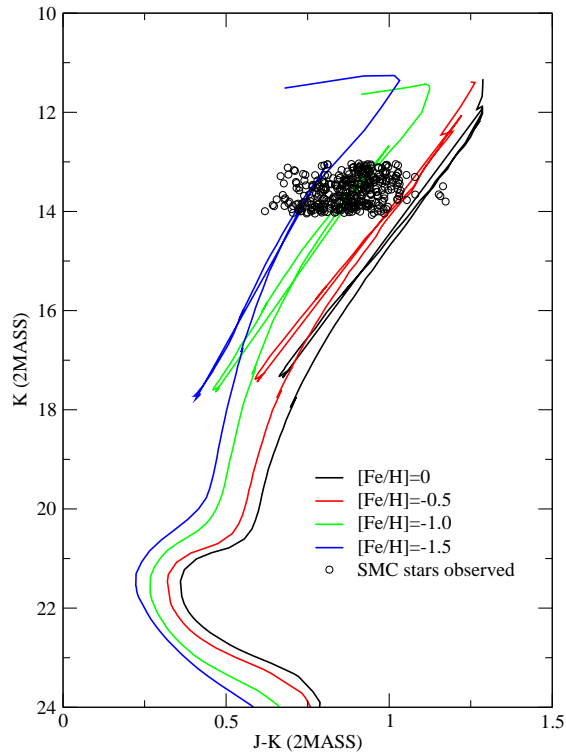


FIG. 1.— The target stars shifted on to Padova isochrones of age 10 Gyr with metallicities as indicated in the legend, assuming a SMC distance modulus of 18.79 mag.

Data for this project were obtained as part of the Bulge Radial Velocity Assay (BRAVA – Rich et al. 2007; Howard et al. 2008, 2009). The BRAVA survey was allocated a series of runs between August 2008 and August 2009 to carry out radial velocity measurements of  $\sim 10000$  M giants in the Bulge of the Milky Way. The allocated times were somewhat sub-optimal for bulge observations and left about 1/3 of each night free, after the Bulge sank to high airmass at about 02:30. We decided to dedicate this remaining time to an exploratory survey to study the kinematics and chemical abundances of K giants in the SMC.

Observations were taken at the V. M. Blanco 4m telescope on Cerro Tololo, Chile, using the Hydra multi-fiber spectrograph. We used the KPGLD grating (790 l/mm, blazed at 8500 Å), with the 200  $\mu$ m slit mask to achieve a resolution of 4200, covering a spectral range of 1800 Å centred on 7900 Å, including the three Calcium Triplet (CaT) lines at 8498, 8542 and 8662 Å. Further details on the survey may be found in the BRAVA paper by Howard et al. (2008). Exposure times for each target were  $3 \times 1200$  seconds.

Targets were selected from the 2MASS database (Skrutskie et al. 2006) as luminous red giants at the distance of the SMC, with  $13 < K < 14$  and  $0.5 < J - K < 1.5$ . The selection range and method are analogous to those used for the Galactic Bulge BRAVA survey. Figure 1 shows our targets overplotted over the Padova isochrones (Marigo et al. 2008) shifted to the assumed SMC distance.

Table 1 shows, in column order, the identification of the fields, their positions of the fields (equinox 2000), their distances from the SMC centre (in kpc, assuming the above distance modulus), the number of stars we attribute to the SMC (see below for the definition of the velocity range we considered), the number of stars with successful redshifts we obtain

and the total number of stars surveyed. Figure 2 plots the positions of the fields on the sky with respect to the SMC (using 2MASS data). We have one field at each of the four cardinal points, at projected distances of 0.9 and 1.9 kpc, and two fields to the East of the SMC, at distances of 3.9 and 5.1 kpc.

We reduced the data by first removing the overscan, trimming and then carrying out bias subtraction. At this point we rejected cosmic rays with the Laplacian Edge algorithm (van Dokkum 2001). We then extracted the spectra using the specialized IRAF package *dohydra* and finally combined all the individual spectra for each star using the *scombine* task.

We derived radial velocities by cross-correlating our data with spectral templates (Tonry & Davis 1979) focusing on the region containing the CaT lines. We then measured the CaT index (Cenarro et al. 2001) for our stars using the *indexf* program (Cardiel 2007) and converted our measurements to [Fe/H] using the fitting functions tabulated in Cenarro et al. (2002), with  $T_{eff}$  and  $\log g$  from the Padova isochrones (Marigo et al. 2008). Our stars are actually comparatively faint, with  $I$  of 16 to 17, plus we often observed after moonrise, so our errors are relatively large:  $\pm 10$  km s $^{-1}$  in radial velocity and  $\pm 0.1$  dex in [Fe/H].

### 3. KINEMATICS

In Figure 3 we show radial velocity histograms for all fields (as marked in the figure legend) and a comparison with expectations from the Besancon model of the Galaxy (Robin et al. 2003), assuming the same selection criteria as our SMC fields and over the 40' field of view sampled by Hydra.

We assume that all stars with heliocentric radial velocity greater than 100 km s $^{-1}$  can be attributed to the SMC, as implied by the distribution of velocities in the Besancon model (Figure 3). In the Northern 0.9 kpc field, the stars follow a Gaussian distribution with  $\langle v \rangle = 152 \pm 26$  km s $^{-1}$ , while the South 0.9 kpc field has  $\langle v \rangle = 160 \pm 39$  km s $^{-1}$ . These values are broadly consistent with previous measurements as tabulated by Harris & Zaritsky (2004). However our East 0.9 kpc field shows a bimodal distribution. The KMM algorithm (Ashman et al. 1994) returns two peaks at 162 and 205 km s $^{-1}$  with 72% significance. In the Western 0.9 kpc field there also appears to be a bimodal distribution, with peaks at 143 and 180 km s $^{-1}$  but at much lower significance. The lower velocity peak is consistent with the conventional SMC recession velocity, while the other peak may correspond to a high velocity component, detected in HI observations (Mathewson & Ford 1984; Stanimirovic et al. 2004).

For the 1.9 kpc fields, the Northern field has  $\langle v \rangle = 147 \pm 26$  km s $^{-1}$ , while for the Southern field the distribution appears to be bimodal with peaks at 156 and 206 km s $^{-1}$  with a 75% significance according to the KMM algorithm. As for the 0.9 kpc field, the Eastern field also appears to show a bimodal velocity distribution, with peaks at 162 and 211 km s $^{-1}$  at a 58% significance level. The Western field is instead consistent with a single component with  $\langle v \rangle = 189 \pm 23$  km s $^{-1}$ . In all these cases we recover the ‘typical’ SMC velocity dispersion of about 25 km s $^{-1}$ .

We also observed two fields to the East, at a distance of 3.9 and 5.1 kpc from the SMC centre. The SMC is clearly present in the 3.9 kpc field. This has a pronounced bimodal velocity distribution, with peaks at 106 and 211 km s $^{-1}$ . While the high velocity component is at approximately the same radial velocity in all eastern fields, and in the Southern field as well, the velocity separation with the lower velocity component appears to increase significantly outwards from the SMC centre.

TABLE 1  
POSITIONS OF OBSERVED FIELDS

Field Name	RA (2000)	Dec (2000)	$R_{SMC}$ (kpc)	$N_{SMC}$	$N_{spectra}$	$N_{targets}$
5001	01:05:42.2	−72:50:31.4	0.96	81	82	105
5002	01:18:33.8	−72:48:41.8	1.91	82	94	101
5003	01:45:44.4	−72:50:30.4	3.90	43	63	81
5004	02:01:31.5	−72:47:17.8	5.06	5	44	62
5005	00:40:47.7	−72:53:36.6	0.88	57	74	98
5006	00:26:30.1	−72:51:44.2	1.93	58	61	108
5009	00:53:01.5	−71:53:26.8	0.94	75	86	117
5010	00:52:40.9	−70:53:43.4	1.94	36	57	91
5013	00:52:34.2	−73:43:53.4	0.90	78	82	112
5014	00:52:57.9	−74:44:43.4	1.91	36	40	100

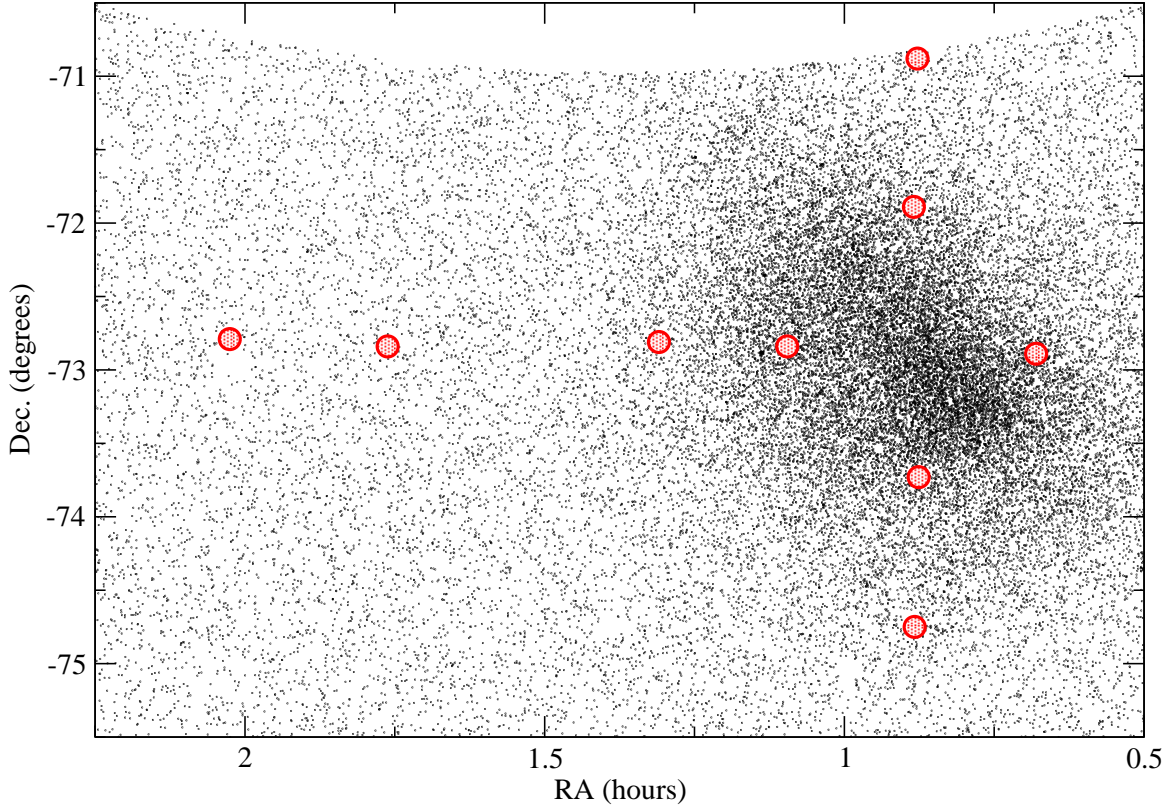


FIG. 2.— Map of the SMC from 2MASS data, using stars with  $13 < K < 14$  and  $0.5 < J - K < 1.5$ . We overplot circles representing the fields observed and whose positions are reported in Table 1.

On the other hand, the SMC contribution is very small to non-existent in the most distant field to the East. This suggests that the edge of the SMC in this direction is close to this field. To estimate this, we first calculated the number of SMC stars in each of our Eastern fields based on the derived completeness and fraction of stars we attribute to the SMC in Table 1. We then integrated a 10 Gyr old,  $[\text{Fe}/\text{H}]=-1.0$  luminosity function from Marigo et al. (2008) and derived the surface brightness of SMC stars in our fields, after correcting

for incompleteness and sampling. We then fit this to a Hernquist profile and extrapolated to a surface brightness of  $26 \text{ mag arcsec}^{-2}$  in  $K$ , which we take, arbitrarily, as the SMC ‘limit’. This exercise returns a distance of 5.8 kpc, unlike what observed by Harris & Zaritsky (2004) along the Magellanic Bridge, and the detection of SMC stars out to about 6.5 kpc to the South of the SMC by Noël & Gallart (2007). These latter stars may of course have been formed and/or tidally displaced from the SMC by the repeated interactions with the

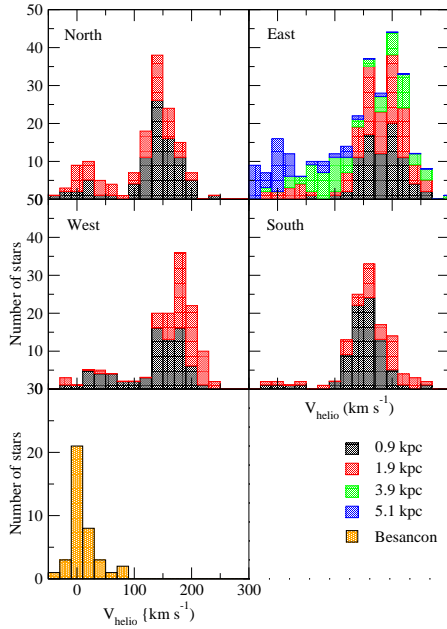


FIG. 3.— Histograms of radial velocities for observed fields. The data are plotted as stacked charts with a different color for each distance surveyed and the colors are identified in the figure legend. We plot the North, South, East and West fields in different panels as identified in the figure. The bottom panel shows the predictions of a Besancon model of the Galaxy for the same selection criteria as our targets and over a single Hydra field.

LMC.

#### 4. METALLICITIES

Figure 4 shows the distribution of metal abundances, from the Calcium Triplet, in the 8 inner fields. At a projected distance of 0.9 kpc from the SMC centre, both the East and West fields show broad metallicity distributions centered at  $[\text{Fe}/\text{H}] = 1.27 \pm 0.05$  with a dispersion of  $0.48 \pm 0.03$  and  $-1.47 \pm 0.05$  with a dispersion of  $0.99 \pm 0.05$  respectively, consistent with previous studies (Piatti et al. 2007a,b; Carrera et al. 2008; Parisi et al. 2008, 2010). The metallicity distribution for the 0.9 kpc field to the North instead appears to exhibit a peak at about  $[\text{Fe}/\text{H}] \sim -1.3$  and another at  $[\text{Fe}/\text{H}] \sim -0.6$ , while in the South the metallicity distribution is also broad and extending to solar or slightly supersolar metal abundances. The metallicity distributions are also similar in the four 1.9 kpc fields, but the higher metallicity stars in the North and South fields are no longer present. All these fields have  $[\text{Fe}/\text{H}] \sim -1.35 \pm 0.10$  with a dispersion of about  $0.65 \pm 0.08$ .

While we do not see a radial abundance trend, as claimed by Carrera et al. (2008) the disappearance of the higher metallicity stars in the outer Northern and Southern fields, with respect to the inner fields, may explain the discrepancy between the claim of Carrera et al. (2008) for a metal abundance gradients and the results of Parisi et al. (2008, 2010) and Cioni (2009). While the majority of the SMC stars follow a broad metallicity distribution with no radial trend, some of the inner fields contain a more metal rich, and presumably younger, population. This would mimic a metal abundance gradient if the bimodality of the distribution is not taken into account.

#### 5. DISCUSSION

The data we present here show that, while the SMC is detected to large distances (about 6 kpc) along the Magellanic Bridge (Harris & Zaritsky 2004) and to the South

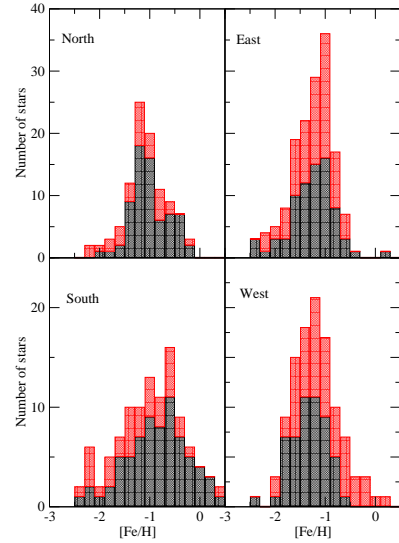


FIG. 4.— The metallicity distribution (measured via the CaT) of stars in the fields at 0.9kpc and 1.9kpc from the SMC centre. We plot our fields as in Figure 3. Identifications are as in the legend in Figure 3.

(Noël & Gallart 2007), we appear to have approached the edge of the SMC in our easternmost fields. We estimate that the SMC ‘edge’ in this direction lies at about 6 kpc from its centre. The shape of the SMC has however been tidally distorted by interactions with the LMC and it has been elongated along the N-S direction (Kunkel et al. 2000). Exploration of the radial and azimuthal behavior at larger distances will be one of the outcomes expected from a wider-field spectroscopic survey.

The kinematics of stars in our fields is complex. There is evidence for the presence of two components in some fields, particularly to the East and the South, i.e. the regions most affected by interactions with the LMC and the Magellanic Bridge: a low velocity one around  $160 \text{ km s}^{-1}$  and a high velocity component at about  $210 \text{ km s}^{-1}$ . Although the evidence is weak, while the high velocity component is at the same position in our 3.9kpc field to the East, the low velocity component appears to have lower velocity. This is reminiscent of the claims for multiple peaks in the HI velocity distribution (Mathewson & Ford 1984; Stanimirovic et al. 2004). Similar bifurcations are also observed in tidal streams. The HI features are often attributed to multiple and overlapping gas shells, but their presence in the stellar distributions, especially in the zones to the East and South closer to the Magellanic Bridge, may favor multiple components models such as those of Mathewson & Ford (1984).

An intriguing possibility is that we are detecting stars from the LMC in the SMC Eastern fields: Munoz et al. (2006) find the presence of LMC stars as far  $23^\circ$  from the LMC centre (which of course lies to the East of the SMC), while Bekki (2008) has argued for the existence of a common halo encompassing the LMC and SMC. Based on the recent study of LMC kinematics by van der Marel et al. (2002), we would expect LMC stars to lie at the position of the second velocity peak we observe in the Eastern fields. This seems somewhat less likely because we find that the secondary peaks in our data contain about the same number of stars as the primary velocity peaks, and therefore appear more likely to be associated with the SMC velocity structure than the LMC. Since our easternmost fields are closer to the LMC than the 0.9 kpc eastern field, we would expect the LMC contribution (if it causes

the secondary peak) to increase ‘outward’ from the SMC, unlike the observations. It is of course very likely that some LMC stars are actually superposed over the SMC, but they can probably be securely separated out only by chemical tagging.

One striking feature we observe in our data is a broad metallicity distribution centered on  $[\text{Fe}/\text{H}] \sim -1.2$ , extending from  $-2.5$  to solar or even slightly supersolar values. This is very similar to what observed in the LMC by Munoz et al. (2006) and in Sagittarius by Monaco et al. (2005) and may suggest a very similar chemical evolution pattern in most dwarf galaxies. In fact the abundance distribution we observe in the SMC is also very similar to that measured for the M31 “giant stream” population, with a peak near  $[\text{Fe}/\text{H}] \sim -1$  and tails to high and low metallicities (Koch et al. 2008). The ingestion of massive galaxies such as the SMC has been invoked to explain the wide metallicity distribution and the presence of metal-rich stars in the M31 halo (see e.g., Koch et al. 2008). In the case of the SMC there is the question of how a galaxy massive enough to host such metal-rich stars could have been accreted by the SMC without more significant disruption of the SMC (but see Tsujimoto & Bekki 2009).

The broad metallicity distribution may instead imply the presence of multiple stellar generations. It is known that the SMC has undergone recent star formation, possibly induced by encounters with the LMC, after a long period of quiescence (Harris & Zaritsky 2004). Carrera et al. (2008) claim that there is a metal abundance gradient in the SMC and suggest that this is due to the presence of younger stars in the centre of this galaxy. We find that the main population of the SMC does not exhibit a metal abundance gradient (Parisi et al.

2008, 2010), but that in the inner fields to the North and South there is a contribution from more metal-rich stars, with peak metallicity around  $[\text{Fe}/\text{H}] \sim -0.6$ . Noël & Gallart (2007) find evidence for an intermediate age population in their fields to the South out to 6.5 kpc, while a younger stellar population is detected by Harris & Zaritsky (2004) along the Magellanic Bridge. The presence of more metal-rich stars forming a separate peak in the inner fields resembles the picture of Carrera et al. (2008) where a recent burst of star formation has led to self-enrichment in the inner regions. The approximate North-South trend is roughly in the directions of the Bridge and Stream features and it is tempting to speculate that the interactions that created these gaseous features are also responsible for the star formation episodes.

A wider and larger spectroscopic survey will allow us to clarify the structure and kinematics of the SMC, explore the existence of metallicity gradients, search for a metal poor halo and detect the presence of streams.

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